

Spitzer Space Telescope Observatory Planning and Scheduling Team

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Abstract—Launched as the Space Infrared Telescope Facility (SIRTF) in August, 2003 and renamed in early 2004, the Spitzer Space Telescope is performing an extended series of science observations at wavelengths ranging from 3 to 180 microns. The California Institute of Technology is the home of the Spitzer Science Center (SSC) and operates the Science Operations System (SOS), which supports science operations of the Observatory. A key function supported by the SOS is the long-range planning and short-term scheduling of the Observatory.

This paper¹² describes the role and function of the SSC Observatory Planning and Scheduling Team (OPST), its operational interfaces, processes, and tools.

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1. INTRODUCTION

The Spitzer Space Telescope is the fourth and final of NASA's great observatories, designed to take images and spectra of a wide range of astronomical objects in the infrared - wavelengths of 3 to 180 microns. Spitzer (Figure 1) consists of a spacecraft, an 0.85-meter telescope and three cryogenically-cooled science instruments; the Infrared Array Camera (IRAC), the Infrared Spectrograph (IRS), and the Multiband Imaging Photometer for Spitzer (MIPS).

Launched from Cape Canaveral, Florida, on August 25, 2003, the mission had planned for a 60 day In-Orbit Checkout (IOC) period followed by a 30 day Science Verification (SV) phase. Spitzer employed an innovative warm launch architecture; the telescope is located outside the cryostat and was at ambient temperature at Launch; the telescope is cooled by He vented from the cryostat, and it was cooled to ~5.6 degrees Kelvin over 45 days. At the completion of SV, Spitzer transitioned into its normal operating mode, and will have completed fourteen months of routine operations as of March 2005.

Spitzer's three science instruments are operated in a discrete number of observing modes (7 specified at launch) which are characterized as Astronomical Observation Templates (AOTs). In order to design an observation, the astronomer chooses a template and specifies a number of parameters that are specific to it. These inputs produce a complete recipe for the commanding needed to carry out the observation on board Spitzer. The resulting fully-specified observation is called an Astronomical Observation Request (AOR) and the parameters are stored in the Spitzer Science Operations Database (SODB) at the SSC along with estimates of the duration of the observation, the volume of data it will generate, etc. The AORs and their resource

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estimates become the fundamental inputs to the Planning and Scheduling process.

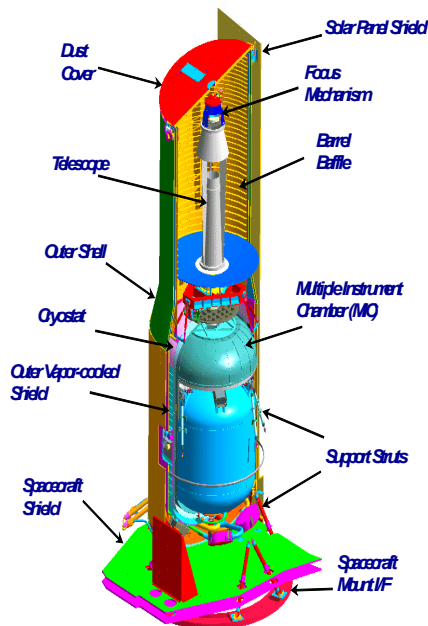


Figure 1. Spitzer Observatory

Operations organization

The Spitzer flight operations organization has two components –the Science Operations System (SOS) and the Mission Operations System (MOS). The Observatory Planning and Scheduling Team (OPST) is in the perview of the SOS managed by the Spitzer Science Center and located at Caltech.

The SSC is responsible for evaluating and selecting General Observing proposals. This function is performed by the Time Allocation Committee (TAC) see Figure 3. SSC is also responsible for providing technical support to the science community, performing mission planning and science observation scheduling, instrument calibration and instrument performance monitoring, data processing and production of archival quality data products, and funding science research (Figure 2). The MOS is comprised of teams located at both the Jet Propulsion Laboratory (JPL) and Lockheed Martin in Denver.

The uplink process starts at the SSC, with the generation of one-week science schedules, which are then sent to the MOS for final command generation, validation, and radiation to the observatory. Data are received from the observatory by the Deep Space Network (DSN) and transferred to JPL where level 1 data processing is done. The data is then sent

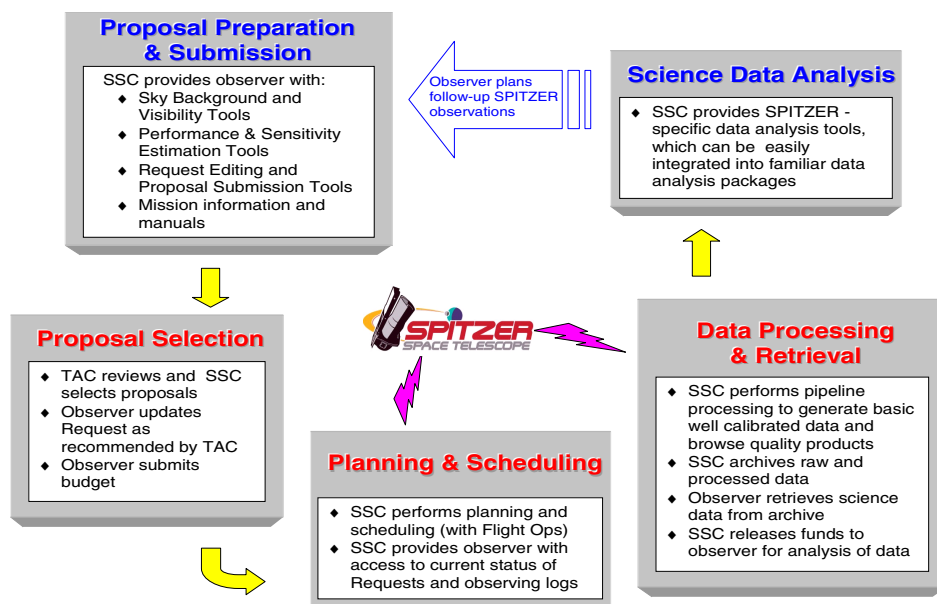


Figure 2. SSC Functions

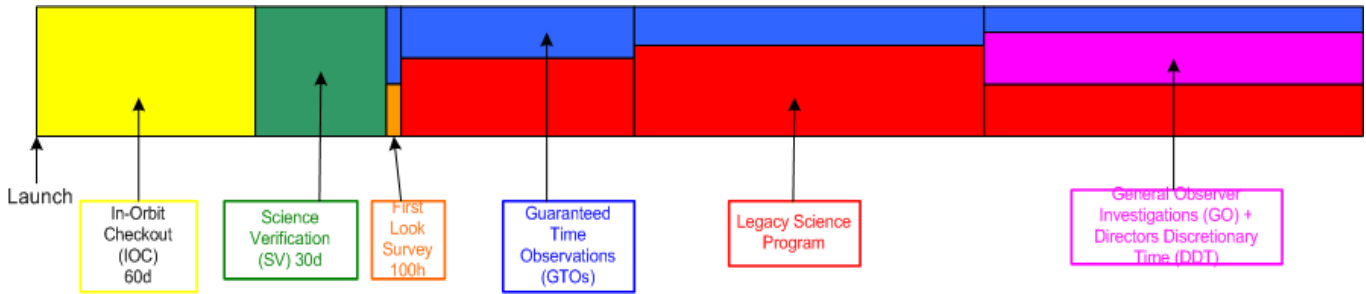


Figure 3 How Time Allocation Committee (TAC) allocated time for Spitzer's first year

to the SSC for science data processing, science product generation, and archiving. The main MOS teams that the OPST interfaces with are the Mission Sequencing team (MST) at JPL and the Observatory Engineering Team (OET) at Lockheed Martin in Denver

1.1 Observatory Planning and Scheduling

A key function supported by the SSC is the long-range planning and short-term scheduling of the Observatory. The Observatory Planning and Scheduling Team (OPST) at the SSC uses software called SIRPASS (Spitzer Integrated Planning and Scheduling Subsystem). SIRPASS is designed to perform both long-range planning and short-term scheduling through generation of command sequence products. SIRPASS uses a version of the Spitzer Science Planning Interactive Knowledge Environment (SPIKE) software developed by the Space Telescope Science Institute (STScI) and adapted by STScI for Spitzer for a portion of the long-range planning function.

Spitzer's science instruments can only be used one at a time, and for reasons of efficiency and maximizing the observatory's life time, there is a preferred ordering (IRAC, MIPS, IRS) and duration (4-12 days) of instrument usage. In Long-range Planning (LRP) this information is folded together with the information about the AORs in SODB to produce a Baseline Instrument Campaign (BIC) for an extended period of time (e.g. one year) that allocates windows of time when each of the three instruments is planned to be available for observations.

Once a BIC is established, the long-range planner also allocates what are called plan windows for each observation. The long-range planning function of SIRPASS assigns "plan windows" to each request in the SODB by intersecting target visibility as a function of time with the availability of a particular instrument (per the BIC), and any constraints associated with the observations. For example, constraints may include requests by observers to acquire data on specific dates, in a specific order, or at specified time intervals. Plan windows allow the scheduler to identify which science requests are available to schedule in the given time period. Plan window updates are usually done approximately once per week in order to keep pace with the frequent modifications and additions to observing programs in the database, as well as to take into account observations that have been scheduled.

Short-term scheduling is the process of filling each week on the observatory with engineering and science activities. There are analogs to the AOR for science instrument engineering, Instrument Engineering Requests (IERs) and spacecraft engineering events Spacecraft Engineering Requests (SERs) and all these types of activities are scheduled by OPST using SIRPASS. SIRPASS uses a variant of the "Greedy" scheduling algorithm to help optimize scheduling of the science observations. A weekly schedule is produced and approved by the SSC Director and the Mission Manager, at which point science sequence files are produced and transferred to the Mission Sequencing Team (MST) at JPL for generation of command products to uplink.

1.2 IOC/SV operations

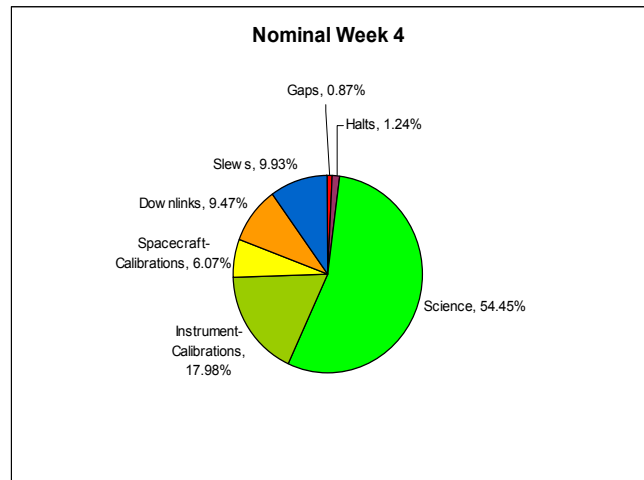
The Spitzer IOC and SV phases were planned to last for 90 days. Ground operations were event-driven and expected to be intense compared to normal operations. IOC/SV campaigns were scheduled much differently than they are in nominal operations. One of the main differences is that an integrated timeline of all spacecraft, engineering and science requests was produced well in advance of launching Spitzer. Many of these activities were dependent on the results of precursor activities. While some activities could be carried out early with a warm telescope, most of the instrument activities required a much cooler telescope and were scheduled later in the IOC/SV period. Rather than building sequences by the week they were built by instrument campaign (each campaign could be from a few hours to a day or so in duration) which allowed more flexibility to respond to changes based on the new data. Rescheduling and re-sequencing had to be flexible and rapid to maximize the productive use of flight time.

The Spitzer flight team completed IOC in 62.8 days and SV in 35.6 days for a total of 98.4 days. The longer duration was due primarily to the three safing/standby events experienced by the spacecraft. One of these events was the “solar storm of the century” on October 28, 2003. The event required the observatory to be idled for two and a half days. Another two days was spent carrying out the solar storm recovery procedures for the science instruments. The completion of the IOC and SV phases within a week of the planned end is a remarkable achievement, and is due to the hard work and dedication of the whole Spitzer project, including the SSC, the MOS, and the instrument principal investigator teams.

1.3 Efficiency

One measure of efficiency is the measure of time spent executing activities directly related to science observations. As reported here, this includes the time spent making science observations and the time used for science instrument (SI) calibrations. It does not include spacecraft (S/C) calibration time, slews, idle time or data downlinks (D/L). As of the writing of this paper, Spitzer has executed 55 weeks of normal operations. The science efficiency has risen steadily over this time period from an average of 68% over the first 8 weeks to an average of 81% for the most recent 8 week period. The Spitzer goal for science efficiency as specified prior to launch was 90% including acquisition slews for science activities, and the project is close to accomplishing that. In addition the efficiency with which that science is carried out is also increasing.

Figure 3: Comparison of Efficiency of an early week vs. a current week



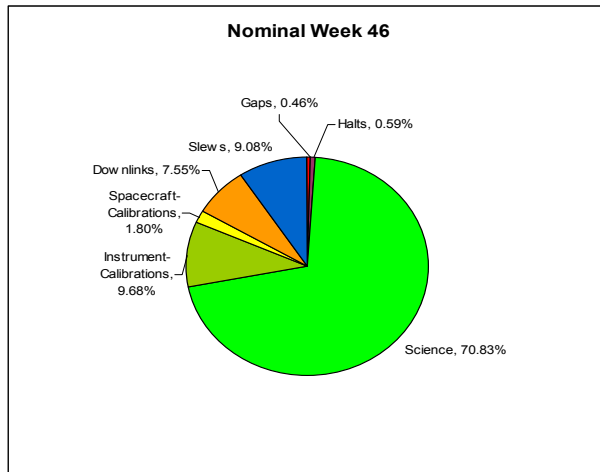
A number of operational changes have been made to improve efficiency, some examples of which follow. The duration and frequency of several spacecraft calibrations have been reduced. A change to the pointing control system maximum torque configuration has been implemented, reducing the slewing time for short slews. The duration of the downlink passes has been tuned to match the downlink volume duration where longer contacts are not needed to support spacecraft engineering commanding. The scheduling algorithm in the ground software has been tuned to do a better job of optimizing slews. Instrument calibrations have been streamlined as the teams have better characterized their instruments. And finally, the OPST has been able to benefit from the months of experience with Spitzer to fine tune procedures to strictly minimize the amount of idle time on the observatory.

Areas of efficiency increase continue to be identified as part of a continuous, deliberate effort to maximize the science return from Spitzer.

1.4 The uplink process

The transition from the IOC/SV rapid, event-driven uplink process to the standard 40 hour week normal operations process was a difficult one. The IOC/SV process was designed to allow for short lead times, while the normal process involves almost six weeks of development time (Figure 4 actuals). It took 12 weeks of normal operations before we fully achieved the standard operations uplink timeline. Since week 16, the uplink process milestones have consistently been met.

The sequence development process involves multiple teams of both the MOS and SOS entities. The iterative review of sequence and command products insures scrutiny by all operational entities for processing errors, violations of flight or mission rules, and adherence to Project policies.



There remain several areas where the scheduling process can be improved. For example, to address the problem of latent imaging on the various instrument detectors, schedulers must currently schedule bright object observations manually, following prescribed rules that are different for each instrument and dependant on the brightness of the object. This is labor intensive and adversely affects the efficiency of the process as well as slew efficiency. Database infrastructure and software updates are planned to flag observations which need this type of special handling. Also, several observation

programs tends to increase slewing and thus reduces science efficiency. Constrained programs also substantially complicate the recovery from any on-board anomaly.

2. TOOLS

2.1 The Spitzer Integrated Resource Planning and Scheduling System

The Spitzer Integrated Resource Planning and Scheduling System (SIRPASS) is an interactive software application for the planning and scheduling of Spitzer Space Telescope (Spitzer) activities. The application is designed to be a software-based assistant to the members of the Observatory Planning and Scheduling Team (OPST) who are experts in the planning and scheduling of Spitzer observations. The application is a Decision Support System that provides an integrated platform for assessing the quality of Spitzer scheduling options. The application aids in scheduling instrument selection, assigns schedule times to specific observation requests, and generates stored sequence products destined for execution on Spitzer.

SIRPASS is an adaptation of Plan-IT-II, a JPL-developed spacecraft activity planning software application. The Plan-IT-II software application has a long history of use at the Jet Propulsion Laboratory, including use on the Mars Pathfinder and Galileo projects. Plan-IT-II supports the modeling of spacecraft activities and their impacts upon a

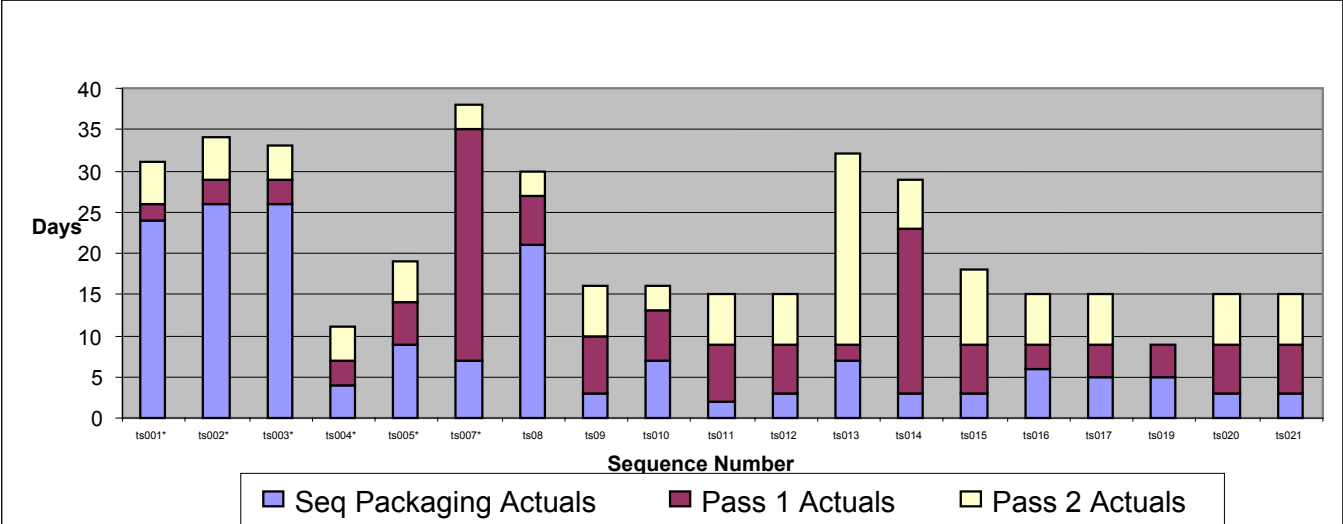


Figure 4: How long the first few weeks took to build

scheduling process with other less constrained observations scheduled around them. The interaction of constrained

domains. Plan-IT-II is developed in Allegro CL, a dynamic object-oriented development environment for ANSI Common Lisp from Franz, Inc.

SIRPASS incorporates a full complement of system-level models and activities. The software includes activity type definitions for all of the approved Spitzer request types, models for each resource whose utilization impacts the schedule, and a variety of integrated models and interfaces that support the tasks and decisions required of the OPST.

Long-range planning is supported by the Spitzer Science Planning Interactive Knowledge Environment (SPIKE) module from the Space Telescope Science Institute along with a variety of reports that detail the often-complex constraint relationships between requests. Short-term scheduling, which forms the majority of the week-by-week OPST tasks, is facilitated through the use of an automated scheduling algorithm derived from the Hubble Space Telescope scheduling operations. Finally, SIRPASS supports the weekly production of formal schedule review and stored sequence products. In order to obtain accurate predictions in support of efficient scheduling, SIRPASS includes a number of independently developed models, including:

The Spitzer Slew Model — An efficient schedule allocates no more time than necessary to the slewing of the telescope from one location to the next. Should too little time be allocated to slewing, the telescope would be in danger of not finishing an observation before an established deadline. The Pointing Control System (PCS) slew model brings the on-board control algorithms into the realm of the ground data system, enabling a variety of ground-based software applications to accurately predict Spitzer slew times. The Spitzer PCS Slew Model is implemented in the C language and integrated into SIRPASS.

The Spitzer PCRS Catalog Tool — The Spitzer Pointing Calibration and Reference Sensor (PCRS) Star Catalog Tool is ground-based software used in the Spitzer Uplink Process to select appropriate stars from the PCRS Guide Star Catalog (GSC). The Pointing Calibration and Reference Sensor allows Spitzer to obtain more accurate pointing by referencing the locations of well-known stars. PCRS calibration activities must be performed periodically during the schedule. In order to not significantly decrease the efficiency of the schedule, SIRPASS uses the Spitzer PCRS Catalog Tool to select a calibration star which is close to the scheduled slew path.

The Spitzer SPIKE Module — SIRPASS supports the long-range planning process through its integration of the Spitzer Science Planning Interactive Knowledge Environment (Spitzer SPIKE) from the Space Telescope Science Institute

(STScI). Spitzer SPIKE operates in one of two major modes. In both modes, Spitzer SPIKE calculates a Plan Window for each request. A Plan Window is a series of time intervals where a request may be scheduled. The request's Plan Window is consistent with the Baseline Instrument Campaign (BIC) and all constraints in which the request participates. In some cases, the Plan Window is empty indicating that the request cannot be scheduled.

The Mars Pathfinder-Heritage Data Model — Several recent spacecraft have inherited the Mars Pathfinder (MPF) flight software architecture. The telemetry model that is part of that architecture includes the Consultative Committee for Space Data Systems (CCSDS) concept of Application Process Identifiers (APIDs)

SIRPASS supports a constraint language similar to that defined for the Space Telescope Science Institute:

Group Within — Perform a set of observations such that no two requests in the set are separated by more than a given duration.

Sequence — Perform a set of observations in a given order, completing the entire set within a given duration.

Chain — Perform a set of observations in a given order with no other intervening activities

Time Window — Perform an observation within the time specified.

Follow On — Perform two observations separated by no more than a maximum duration and no less than a minimum duration.

Interfaces:

Deep Space Mission System — The Advanced Multi-Mission Operations System (AMMOS) is the data system developed by the Deep Space Mission System (DSMS) for handling the various command, telemetry and data analysis required by spacecraft systems. The AMMOS defines the interfaces and systems by which commands are sent to the spacecraft and telemetry is received and processed by the ground. The SIRPASS software application contains modules that translate the schedule of Spitzer observations into a format that can be processed by the Uplink segment of the AMMOS system. Communication with the Uplink Segment of AMMOS is usually accomplished via file-based interfaces.

Science Operations Database — The Science Operations Database (SODB) at the Spitzer Science Center stores information about all requests for Spitzer observations. The

SODB is central to all science operations and contains a summary of all tracking and status information related to a given request. The SIRPASS software application obtains information about requests for observations from the SODB and provides schedule and status updates to the SODB.

The SODB classifies requests for observations into three categories:

Instrument Engineering Requests (IERs) are instrument-specific calibration activities or other activities that are not specifically part of an observation program proposed by the Infrared Astronomer community.

Astronomical Observation Requests (AORs) are instrument specific requests for scientific observations and are associated with an observation program proposed by the Infrared Astronomer community.

Spacecraft Engineering Requests (SERs) are calibrations and other types of requests that serve Spitzer as a whole and are not generally tied to a specific instrument.

We can categorize the information stored by the SODB as follows:

General — Includes title, program and observer affiliations, comments, instrument, and observation type.

Resource Estimates — Includes predicts of execution duration and telemetry data volume.

Target Specification — Includes specification of initial and final location observation.

Scheduling Information — Includes scheduled request start and stop times and inter-request constraints.

2.2 CAVE/AIRE

The Client AIRE Visibility Expeditor (CAVE) tool is also used extensively during scheduling. It performs many tasks. From a scheduling perspective the program is run three separate times to produce different results. Each level of execution is fondly call a “baking”. The first baking consists of running CAVE to create visibility windows for each observation. Observer Support runs the first CAVE baking (CAVE=1) on accepted science programs, while the scheduler runs it for calibration requests. During the second baking CAVE is used to create fairly realistic slew durations for each observation that could potentially be scheduled in that week based on the week boundaries. After the schedule is firm a third baking of CAVE is done to even further refine the estimates based on the observations actual schedule time and the position of the

activity that proceeds it. CAVE=3 also generates all the necessary files for each observation that are eventually packaged by the scheduler using SIRPASS.

3. LONG-RANGE PLANNING

3.1 Spitzer Baseline Instrument Campaign (BIC)

One fundamental aspect of the Spitzer observatory is that only one instrument can be powered up at a time. The planning consequence of this is that one must plan in advance which instrument will be on at a given time. This manifests itself in a set of Instrument Windows, which are simply time intervals during which a particular instrument is on. A long-range, planned set of such windows is called a Baseline Instrument Campaign (BIC).(Figure 5).

Sample Nominal Operations Baseline Instrument Campaign by Week							
Week #	IRAC	MIPS	IRS				
	Th	Fr	Sat	Sun	Mon	Tue	Wed
21	15	16	17	18	19	20	21
22	22	23	24	25	26	27	28
23	29	30	01-May	2	3	4	5
24	6	7	8	9	10	11	12
25	13	14	15	16	17	18	19

Figure 5: Sample Baseline Instrument Campaign (BIC)

About two years prior to launch, work was begun on planning the initial “draft” BIC based on instrument characteristics and planned science observations. The first attempt was based on two main assumptions: (1) Spitzer scheduling should be able to accommodate very tightly constrained observations (e.g., ones that can only be observed in a 12-hour window or never), and (2) the total instrument window durations should be equal for the three instruments over a six month period.

This led to BICs which had instrument windows as short as 2 hours and as long as 30 days, in more or less random orders. This was unacceptable for a number of reasons. Primarily, very short windows are inefficient or impossible, since instrument calibration and performance monitoring can by themselves take up to 12 hours. Further, the Instrument Support Teams pointed out that very long campaigns led to some instruments being inactive for long periods of time (a month or more), which could lead to degradation of the instrument. Also, anchoring the BIC system to very few highly constrained observations

exaggerated their importance, while failing to account for more important observations that were not so constrained.

More requirements were needed to build acceptable instrument windows, and therefore a BIC. It was decided to use a regular, cyclic pattern of windows whose relative sizes reflected the durations of observations for each instrument. The overall cycling was limited to prevent any one instrument from being off for too long. Finally, it was pointed out that using the instruments in a particular order minimized thermal cycling, thus reducing He usage.

After feasibility testing of various schemes, it was decided that the best results were obtained with a BIC of instrument window lengths 9-8-6 days (IRAC-MIPS-IRS). This reflected the appropriate ratios of observation durations for the beginning of Nominal Operations, and it had the appropriate ordering for thermal optimization. This was the initial BIC pattern going in to Nominal Operations.

The BIC was always meant to be a dynamic entity, responsive to observational needs. As can be seen from above, the overall pattern was designed to be optimal. But changes can and have been made when circumstances warrant.

The usual need arises from long, connected sets of observations that must all be done one after another. There have been times when such sets have overfilled planned instrument windows. The response then has been to lengthen the affected instrument window. This is done at the expense of subsequent instrument windows in an effort to regain the prior BIC pattern within a few campaigns. The alternative would be to have the change “domino” down for the next six months. This would result in dozens of unnecessary changes to instrument windows far in the future. Moreover, some of the future windows may have been planned to accommodate other long, connected sets of observations, and changing them would obviate that effort.

In nominal operations the main purposes of the BIC are to ensure to the extent possible that the science observations are done proportionately to their durations by instrument (otherwise we might run out prematurely) and to accommodate observations that are difficult to schedule that would otherwise not be possible to schedule.

Spitzer’s nominal operations sequences are one week long, thus planning, including long-range planning, takes place on a weekly basis. The primary output of long-range planning is simply a list of requests that the short-term scheduler needs to include in a given week.

Long-range planning takes place roughly six weeks prior to the uplink of a given sequence, thus part of a week’s long-

range planning task is simply to update the previous long-range plan by a week.

The major tasks of the long-range planner are to make sure that large constrained sets of observations can indeed be scheduled, make sure that conflicts among programs are resolved, and keep track of which requests must be scheduled, either to satisfy constraints to previously scheduled requests or to avoid missing the ends of request visibility windows.

Inputs to long-range planning include visibility window and constraint information from the Science Operations Database, the BIC, weekly database status reports provided by the Observer Support Team, and lists of requests that are considered to be committed as they are constrained to requests scheduled in previously uplinked schedules.

3.2 Large Constrained Sets of Observations

There have been a number of programs consisting of dozens of hours of observations, all of which need to be performed in a single instrument campaign. These observations can dominate a campaign, and some care needs to be taken to ensure that the observations will actually fit into the campaign. The BIC is updated several months prior to request execution and should take such programs into account, but there may be unforeseen problems (including changes that have been made in the past few months). One function of long-range planning is to make sure that such programs actually fit in the instrument campaign as intended. If there is a problem, there is still time to make minor modifications to the BIC. Changing the boundaries of the instrument windows becomes a major nuisance if done during short-term scheduling.

In some cases, long-range planning has included determining optimal AOR lengths, so that long programs could be scheduled more efficiently.

3.3 Highly Constrained Observations

Observations with tight time constraints are generally moving targets that have small visibility windows. These have included observations of satellites of planets or of a single planet at various orientations. Long-range planning addresses these in particular for two reasons: it is best to schedule these prior to the scheduling of less constrained requests, and there is a risk of such requests not being scheduled unless special attention is given to them.

In some cases, the required schedule time for a highly constrained observation may fall during a downlink. This problem is unlikely to be noticed prior to long-range planning. Discovering it at this point keeps most of the options for solving it open. These options include

products. There are two passes allocated to this process so that problems uncovered on the first attempt can be resolved.

4.2 Beginning the Build Process

The sequence development time is divided into three parts: sequence packaging, sequence generation pass 1, and sequence generation pass 2.

A number of inputs are required to build a flyable schedule. These inputs include the current BIC, IERs and AORs which comprise the instrument calibration activities for that week, along with their associated scheduling instructions, which are provided by the Instrument Teams (ISTs); and Spacecraft Engineering Requests (SERs) which the scheduling instructions and/or actual metadata are provided by the OET. It is assumed that any unscheduled science AOR with the “available” status in the database is eligible for scheduling. (It is the responsibility of the observers to request that AORs that are to be modified be put on hold.) The scheduler also needs the most up-to-date DSN Station Allocations File, and Spitzer ephemeris file, as well as a final conditions file from the previous week. Lastly, they should have compiled a list of “must-go” requests as previously described.

4.3 Scheduling Instrument and Spacecraft Calibration Activities

During the normal process of scheduling, certain standard SIRPASS-generated SERs (downlink starts, stops, and routine pointing control system calibrations) are put onto the timeline first; these SERs outline a “skeleton” plan for the Week.

Spitzer Scheduling Process

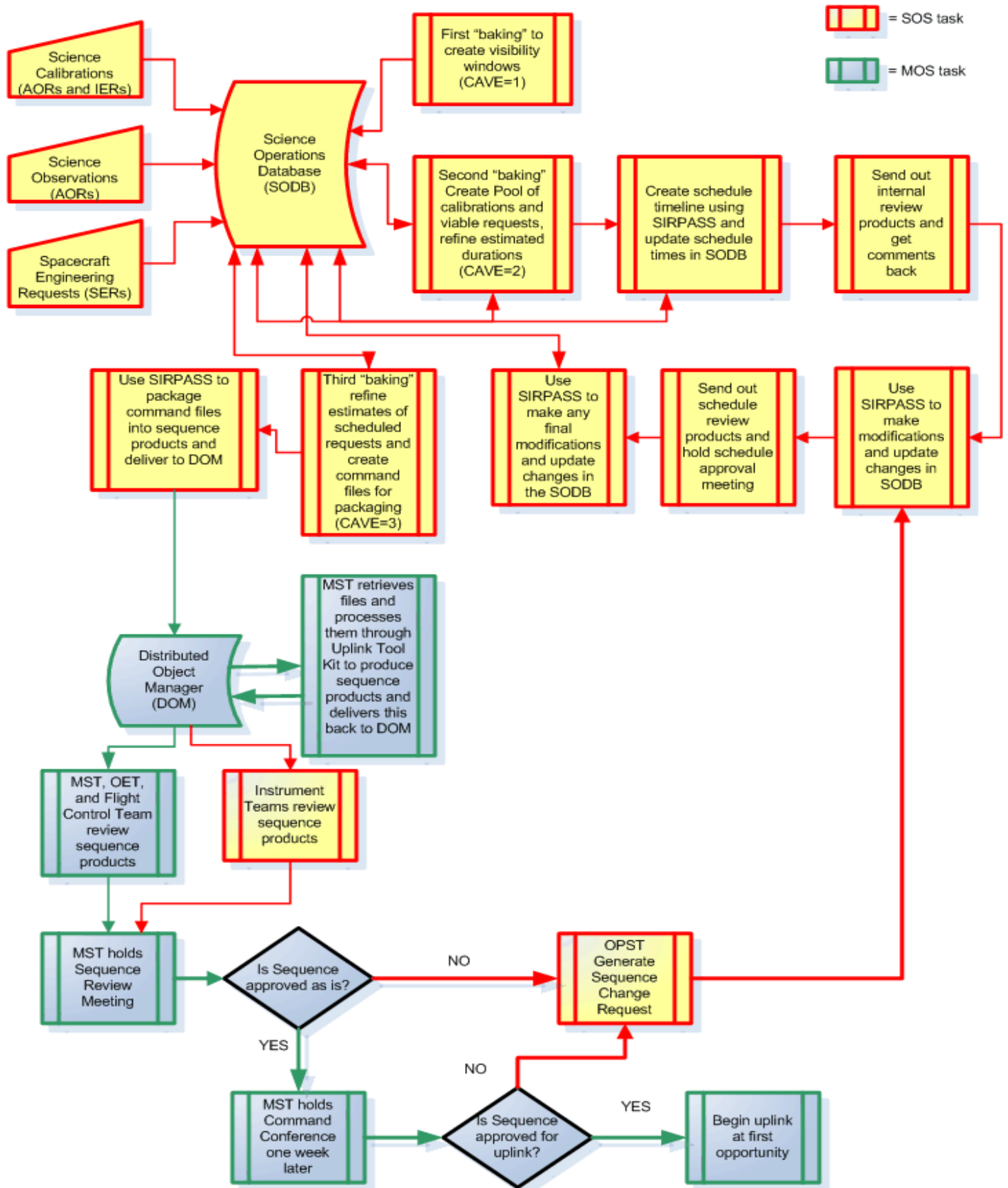


Figure 8 Flow chart the scheduling process

The instrument teams deliver one copy of each their calibration requests in the form of AORs and IERs to the Operations Network, along with instructions on how they are to be used. Some of these activities are done multiple times so it is up to the scheduler to make the necessary copies for that campaign, ingest them into the database and create visibility windows for the ones that have targets by running the first baking of CAVE.

Once the calibration requests have their visibility windows they are ready to be put into a scheduling pool. The scheduling pool is created in SIRPASS. By creating a scheduling pool the flags for each request are set to “selected” in the database, thus preventing another scheduler from inadvertently scheduling them. After the requests are put into a pool the second baking of CAVE is run, in order to obtain a refined estimate for the possible scheduling time, i.e., the start and stop times of the sequence as boundaries. This allows a more accurate estimation of the duration of each request to be calculated. Subsequently, the instrument calibration requests and any special SERs are scheduled on the SIRPASS timeline per their respective instructions.

4.4 Scheduling Science

A complete list of “must-go” requests to be accomplished must be obtained before the actual process of scheduling science can begin. As previously stated a “must go” list contains any high priority science, any observations with expiring plan windows, or observations constrained to previously scheduled requests.

The first step to scheduling science is to use SIRPASS to create a scheduling pool of all the science observations in the database that could potentially be scheduled during the week that is being built. Typically, schedulers only work with one pool, so these requests are added to the pool that already contains the calibration requests and any SERs. The available science requests have already been processed once through AIRE (by the Observer Support Team as they are delivered from the observer) to create the visibility windows (a necessary step before the creation of plan windows), but, just as was done previously for the calibration requests, these must be processed by AIRE a second time in order to narrow the potential schedule time down to the Week currently being built.

Scheduling science on the timeline while respecting all the constraints and calibration periodicities is a difficult task which is sometimes better left to the automated scheduling algorithm, Greedy; however, manual scheduling is frequently necessary due to the afore-mentioned “must-go” requests. Typically all “must-go” science is scheduled by

hand prior to running Greedy to fill in the week. The Greedy algorithm will schedule science around the IERs, SERs, and AORs already on the timeline. The algorithm weighs the benefits and penalties of scheduling each activity in a particular place. It picks a “winner” and schedules it in that place. Some of the characteristics considered are, for example: potential slew required, expiring plan window, and constraint adherence.

After all calibrations and science requests are scheduled the timeline is checked and any conflicts or constraint violations are resolved. Next, the scheduler must obtain updated ephemerides for any small moving targets (comets, asteroids, etc.) which are to be executed in that schedule. This is done through the JPL Horizons service, which provides ephemerides for solar system objects given the NAIF ID of the object and start and stop times for the file. The updated ephemerides must be added to the Operations Network “Point of View”, so that the uplink software will be able to reference the new ephemeris for each moving target in the sequence, in order to properly command the pointing control system.

4.5 Optimization of a Schedule/ Schedule Approval Process

At this point the scheduler generates a set of reports using SIRPASS and sends them out to be reviewed by the appropriate parties. The reports contain information about the requests currently scheduled on the timeline, including start and stop times, predicted slews between requests, constraint violations, targets, positions, calibration periodicities, etc. This schedule is considered to be a “draft version”, and may be changed during the review process. The first step of the review process is an internal SSC review is performed by the instrument teams and the Observer Support Team. Comments are given directly to the scheduler who makes any necessary changes. At that point the Schedule Review reports are sent to a wider distribution including OET, MST and the Mission manager and SSC director. These reviews take place prior to the Schedule Approval meeting, which is typically held at 9:00 AM on the third Thursday following the start of the build. Any further issues are brought up at the Schedule Approval meeting. Typically there are minor adjustments to be made prior to delivering products to JPL. These may include adding and/or deleting specific science AORs, usually at the request of the observer, re-ordering requests to decrease slew time, changing parameters in a block call, or adjusting the placement of calibration requests. The delivery from OPST to MST is scheduled to occur on the third Friday following the beginning of the build process, therefore the scheduler has more than a day to make any requested changes before delivery. If the changes are substantial, the scheduler generally will request an extra review by those

parties who requested the changes before products are delivered to JPL.

4.6 Delivery to MST/Passes 1 & 2

After the schedule is approved, CAVE is run a third time. This third “baking” further refines the estimated duration based on its actual schedule time and creates expansion files for each request. These scheduled requests are then read back into SIRPASS and the schedule is once again checked for conflicts. SIRPASS is then used to package the schedule into master sequence products, which consist of a set of human-readable text files containing a week-long series of commands to the spacecraft and the instruments. The master sequence products are put into a tar file that is delivered to JPL via a transfer process involving SSC scripts which move the products from the SSC file system onto a server where JPL scripts move the tar file into the JPL domain and ingest it into the project database (DOM).

The MST uses a set of software tools called the Uplink Toolkit to convert the delivered sequence products into binary format and simultaneously perform flight rule checking. There are two iterations allocated to this process so that any problems uncovered during the first attempt can be resolved. The two cycles of processing, review, and correction may take up to a week and a half. The last step is the Command Conference for final approval of the sequence prior to uplink. The uplink window opens on the Friday preceding the Wednesday on which the sequence begins execution; a normal week-long sequence is generally broken up into several separate binary files which will be radiated to the spacecraft during the brief periods of contact with Spitzer, which are separated by 12-14 hours. This process may take a couple of days.

4.7 Overlapping development cycles

Due to the five-week development cycle plus the execution week for each sequence, at any given time there are a number of sequences at different stages of the process.

- Week N is executing and being monitored
- Weeks N+1 and N+2 are in the sequencing phase
- Weeks N+3, N+4 and N+5 are in the scheduling phase
- Weeks N+6 and onward are affected by long-range planning updates.

As a specific example, assume that today is Monday, and Nominal Operations Week 45 is at the very beginning of this process, which means that all calibrations for Week 45

are due to be delivered by the end of the day. What are the other schedulers doing today?

The Week 44 scheduler has placed all of the instrument and spacecraft calibrations on the timeline and is entering the science scheduling phase.

The scheduler for Week 43 has finished (or nearly finished) the first draft of the science schedule and will shortly send out internal review products to the ISTs and OST, if he or she has not already done so, as the MST Kickoff for Week 43 will take place tomorrow, and Schedule Approval meeting for Week 43 will occur at 9:00 AM this coming Thursday.

In the meantime, sequence products for Week 42 were sent to JPL at the end of the previous week for processing via the Uplink Toolkit, and the Pass 1 binary sequence products for Week 42 will be reviewed shortly; if there are any problems, the Week 42 sequence may undergo a minor rebuild during the window allotted to Pass 2. The scheduler for Week 42 is preparing for the Pass 1 sequence review to be held later this week.

Week 41 has already gone through the Pass 2 process (if it was necessary) and will have its Command Conference later this week. The scheduler for Week 41 will change the uplink status of the Week 41 scheduled requests after the products are approved for uplink at the Command Conference.

Week 40 has been uplinked to the spacecraft over the weekend, and will begin execution on Wednesday, when the Week 39 sequence, which is currently running, finishes. The schedulers for Weeks 39 and 40 will only be required to make adjustments to these sequences if there is an anomalous event on the spacecraft, such as an entry into standby or safe mode, or in the case of a Target of Opportunity (ToO), or a missed DSN pass. These cases are described below.

4.8 Testing

Although it has been more than a year since the launch of Spitzer the OPST is frequently required to support ongoing testing. The Spitzer uplink software system is highly complex; whenever there are software changes or upgrades of any kind to the uplink system, project management requires that test sequences be built and run on the simulator in Denver (at Lockheed Martin), before the new version of software is used to build flight products.

Another reason to develop test sequences is in support of the development of new procedures; a good example of this would be the Multi-Instrument Target of Opportunity,

briefly mentioned above. Since only one of Spitzer's instruments can operate at any given time, if a rare or important astronomical event occurs, which may need data to be taken by all three instruments on a short time-scale (rotating three instruments in a matter of hours, for example), the OPST, MST, and OET must have validated procedures in place to deal with it.

4.9 Unusual Situations

Anomalies- The Spitzer Mission has been quite successful and relatively anomaly-free since launch in August 2003; however, there have been a couple of safing and standby events which required rapid response and a high degree of coordination between the various Uplink teams to get the observatory back on line quickly. During such an event, the Flight Control Team communicates with the spacecraft, which, under these circumstances, will be broadcasting via the Low-Gain Antenna, while the OET and others attempt to diagnose the problem and come up with a solution. Once the OET has a good estimate of when they will begin the recovery effort to come out of safe or standby mode, OPST will start the process of building the "recovery master sequence", which is usually a truncated version of the master currently on board.

For example, if the spacecraft entered into either standby or safe mode after the master sequence for any particular week had been executing for 24 hours (assuming that the process of diagnosis and determining the appropriate solution may take a full day or longer), the sequence might be rebuilt exactly as before, but with the first 3 days missing. This would result in a shortened master sequence (4 days long instead of 7 in this example), which would begin to execute immediately after a specific downlink pass identified by the OET.

The normal processes and procedures for this emergency build remain in place to the extent that the rapid turnaround time-scale allows; the OPST member responsible for the rebuild, along with members of other teams (OET, ISTs, MST, etc) are required to check the products for problems prior to delivery to MST, and again after the MST has created the binary version of the sequence.

Missed DSN Pass - Another anomalous occurrence to be considered is the instance of a missed DSN pass. Due to the high data volume produced by MIPS, this can be a potentially serious issue. One method for extending a subsequent pass has been developed using a strategy which allows for the replacement of a portion of the sequence on board. The master sequence calls and spawns numerous other processes as it runs, including shorter, relative-timed sequences (generally referred to as slave sequences), which

in turn call some fraction of the hundreds of science and calibration requests that are scheduled in that Week. It is possible to construct a shortened version of a slave which contains a call to the downlink stop block that has been moved later in time, in order to extend the downlink pass in question. The replacement slave sequence is then uplinked to the spacecraft and the original version is deleted, before the current master sequence has issued the call or spawn for that particular slave sequence.

Targets of Opportunity - Targets of Opportunity (ToO) are transient phenomena whose exact timing and/or location on the sky are uncertain at the time of the proposal submission. Targets of Opportunity have already occurred in the year since Spitzer was launched, and are expected to occur in the future. Those which have happened in the past were either inserted as last-minute changes to the schedule (during Pass 2), or dealt with using the slave replacement method described above, which allows a portion of the science and/or engineering content to be changed in an ongoing master sequence.

There is a type of ToO which has not been encountered to date, but is expected to occur within the next few months: a science observation which requires that the current instrument be turned off so that one (or more) of the other instruments may be used. Again, as in the standby or safe mode recovery processes, OPST, MST, and OET must respond rapidly, with a very short turn-around time (generally 48 hours or less), while still following procedures and allowing for some kind of review by the appropriate teams. Several techniques were tested and evaluated for feasibility and the adopted approach is the Master Replacement as described above in the anomaly section and has been successfully used during recovery from safe or standby, except that in the case of a ToO, the rebuilt master would not only be truncated, but the science and engineering content would be significantly different (swapping rapidly between the various instruments).

5. SUMMARY

Since Launch in August 2003, sequences produced by the OPST have been sent to JPL, packaged by the JPL flight operations system and executed on the Observatory with a very high degree of success, and with only very minimal and infrequent problems. Downlink products generated by flight system have been processed at the SSC, and distributed to the astronomical community resulting in very significant amounts of information being added to the understanding of the infrared universe.

The Spitzer Space Telescope has a predicted productive life of five plus years and will continue to add to its already highly regarded successes.

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BIOGRAPHIES

Stephen J. Barba is the OPST Team Lead since Launch minus 90 days. Prior to that he worked at JPL as a Senior Systems Engineer in spacecraft simulation, high performance computing and communications environments, Flight Operations.

Lisa Garcia worked for 15 years at the Jet Propulsion Laboratory on. She worked on operations teams for both the Galileo and Topex mission, most recently as a Remote Sensing Design Engineer. She Joined SIRTF in 1999 as a block author, developing all of the on board science blocks for SIRTF. She continues with block maintenance as well as being a scheduler for the Spitzer Operations Planning and Scheduling Team.

Deborah Levine is the Operations Scientist for the Spitzer Space Telescope Science center. She originally studied physics and worked briefly as an Infrared Engineer for Boeing Advanced Systems Co. She received her Ph.D. in astronomy in 1995 from UCLA, studying the motions of water masers near our galactic center. Her current research interests include the centers of nearby galaxies and the study of planetary nebulae. She has been involved in user support and science operations of space based

infrared astronomical instrumentation since 1989 at the Infrared Processing and Analysis Center in Pasadena, CA.

Doug McElroy graduated from the California Institute of Technology with a degree in Astronomy in 1974. He went to Arizona State University where they were starting an astronomy section in their Physics Department. After obtaining his M.S., he started working at Kitt Peak National Observatory, where he did his thesis work. He obtained his Ph. D. in 1981. That year, he accepted a postdoctoral appointment at the University of Minnesota. In 1983, he was hired for a staff position at the newly-opened Space Telescope Science Institute (STScI) in Baltimore. He worked in, and later headed the Planning and Scheduling section at STScI until 1996. In that year, He accepted a position at the Jet Propulsion Laboratory to work on the Cassini Mission. He did so through launch and the early cruise phase of the mission. In 2000, he was asked to work on the SIRTF Mission (later Spitzer Space Telescope), so he moved to the Caltech campus to work at the Spitzer Science Center where he is currently on the Observatory Planning and Scheduling Team for the Spitzer Space Telescope.

David Mittman designed and implemented the Spitzer Integrated Planning and Scheduling Subsystem (SIRPASS) software as part of the Spitzer Science Center (SSC) Uplink Team. He is also a member of Spitzer's Observatory Planning and Scheduling Team (OPST). Before joining the Spitzer project, he designed and implemented the Mars Pathfinder adaptation of the Jet Propulsion Laboratory's Plan-IT-II scheduling application that was used for planning and scheduling Mars surface operations for the Mars Pathfinder lander. Mittman would like to thank Curt Eggemeyer of the Jet Propulsion Laboratory for his vision in developing the core Plan-IT-II software application.

JoAnn O'Linger Not available

Steven Tyler is a member of the Spitzer OPST. He has worked in development and operations on many JPL projects, including the Wide Field/Planetary Camera, the Superfluid Helium and Drop Dynamics experiments, the Interactions Measurement Payload for Shuttle, the DSN Antenna Controller, the Tropospheric Emission

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